

# ALICE Measurements in p-Pb Collisions: Charged Particle Multiplicity, Centrality Determination and implications for Binary Scaling

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## Abstract

Measurements of particle production in proton-nucleus collisions provide a reference to disentangle final state effects, i.e. signatures of the formation of a deconfined hot medium, from initial state effects, already present in cold nuclear matter. Since many initial state effects are expected to vary as a function of the number of collisions suffered by the incoming proton, it is crucial to estimate the centrality of the collision. In p-Pb collisions categorization of events into different centrality classes using a particle multiplicity distribution is complicated by the low particle multiplicities and the large multiplicity fluctuations. We present ALICE measurements of particle production in p-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, including the pseudo-rapidity and transverse momentum dependence, we discuss the event classification in centrality classes and its implications for the measurements of nuclear modification factors.

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## 1. Introduction

Proton-lead collisions are an important component of the LHC heavy-ion program for their reference role in the understanding and interpretation of the nucleus-nucleus data, to disentangle final state effects, signature of the formation of a hot QCD matter, from initial state effects, already present in cold nuclear matter [1].

Since many initial state effects are expected to vary as a function of the impact parameter of the collision, it is crucial to estimate the centrality-dependence of various observables, including multiplicity and transverse momentum, and to categorize each event according to its centrality. One then needs to determine  $N_{\text{coll}}$  for each centrality class.

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In this proceeding we present and discuss the ALICE strategy to measure centrality in p-Pb collisions and understand the dynamical bias generated when ordering events according to their centrality.

ALICE has measured the nuclear modification factors  $R_{pA}$  in minimum bias collisions [2], where the average p-Pb overlap function  $\langle T_{pA} \rangle$  is determined by total geometric p-A cross-section. Nuclear effects in p-A collisions should be quantified by a comparison of the p-A results to an incoherent superposition of p-nucleon collisions. To make these measurement centrality-dependent, event classes have to be defined using centrality estimators, that can be either particle multiplicity or energy deposited in a given pseudo-rapidity region. For each centrality class, two independent questions need to be answered, namely: how many collisions ( $\langle N_{\text{coll}} \rangle$ ) occur in that sample? and how unbiased are the nucleon-nucleon collisions?

To determine centrality we compare the signals in different ALICE detectors, covering various rapidity regions, which are sensitive to different kind of physics. Particle production measured by detectors around mid-rapidity can be modeled with a negative binomial distribution, while the zero-degree energy of the slow nucleons emitted in the nucleon fragmentation requires more sophisticated models [3, 4]. The main estimators used for centrality are:

- CL1 ( $|\eta| < 1.4$ ): denotes the clusters measured in the Silicon Pixel detector
- V0A ( $2.8 < \eta < 5.1$ ): is the amplitude measured by the VZERO hodoscopes on the A-side (the Pb-remnant side),
- V0M: is the sum of V0A ( $2.8 < \eta < 5.1$ ) + V0C ( $-3.7 < \eta < -1.7$ ) ,
- ZNA: is the energy deposited in Zero-degree neutron calorimeter on the A-side.

Using these estimators we are sensitive to the reaction products of p-N collisions, the Pb fragmentation products that go mainly in the direction of the Pb beam (towards V0A) and the so called slow nucleons from evaporation and knock-out that are emitted into the very forward directions and are detected by the zero degree calorimeters.

## 2. Determination of $N_{\text{coll}}$

### 2.1. NBD-Glauber fit for charged particle multiplicity

For multiplicity measured by detectors around mid-rapidity, the centrality is defined by an analogous procedure to what has been done for Pb-Pb [5]. The measured multiplicity distribution is divided in percentiles of the hadronic cross-section. The distribution  $P(N_{\text{part}})$  is calculated with a p-Pb Glauber-MC [6]. For each  $N_{\text{part}}$ , the multiplicity is calculated according to a Negative Binomial Distribution (NBD). The NBD parameters are fitted to the measured distribution. Then the  $\langle N_{\text{coll}} \rangle$  are calculated for each centrality class. Figure 1, on the left, shows an example for V0A. The same fit procedure is applied for

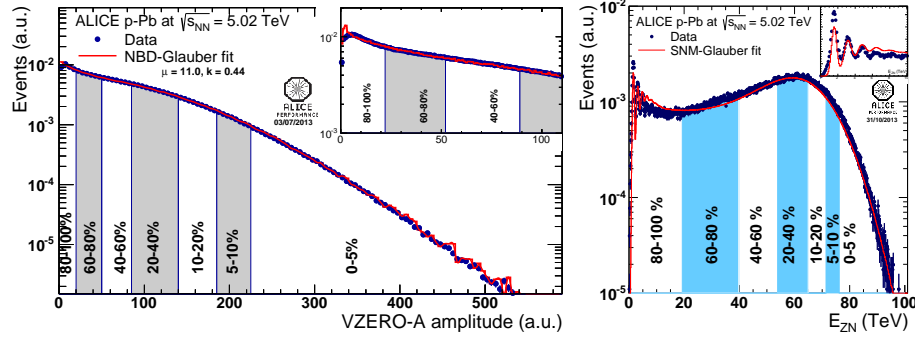


Figure 1: Left: Sum of amplitudes in the VZERO-A scintillators. Right: neutron energy spectra measured in the ZN-A calorimeter. The distributions are compared with the ones obtained from the NBD-Glauber and the SNM-Glauber fit respectively. Some centrality classes are indicated in the figure.

the distribution of CL1 and V0M. The obtained values for  $N_{\text{coll}}$  are similar for different estimators. The systematic error was estimated by varying Glauber MC parameters. We performed a MC closure test with HIJING to confirm the correctness of the approach. The maximum difference between the various estimators is smaller or consistent with the established uncertainty and with the difference between using a multiplicity estimators, or for centrality classes obtained by dividing the impact parameter distribution in percentiles.

## 2.2. SNM-Glauber fit for zero-degree energy

With a totally different approach, the zero-degree energy measured in the ZDC can also be used to extract the number of collisions. The ZDC measures the slow nucleons emitted in the Pb-fragmentation process. For this purpose, a more sophisticated model for particle production, the Slow Nucleon Model (SNM) [3, 4]. Slow nucleons are classified from emulsion experiment into black particles (the low energy target fragments emitted by evaporation) and grey particles (the soft nucleons knocked out by wounded nucleons). The features of emitted nucleons seem to depend weakly on the projectile energy. This indicates that the emission of slow particles is mostly dictated by nuclear geometry. Therefore we follow a parameterization of results from low energy experiments, which describes the proportionality of the soft nucleons to  $N_{\text{coll}}$ .

This model is coupled to the Glauber model which provides the distribution of  $N_{\text{coll}}$ . The results are shown in Figure 1, on the right, where the Monte Carlo Glauber + Slow Nucleon Model distribution are compared to the distributions measured. The ZN-A spectrum is reasonably described by the model. Despite of saturation, which occurs at central events, slicing the events with the ZN still provides a distinction in centrality classes.

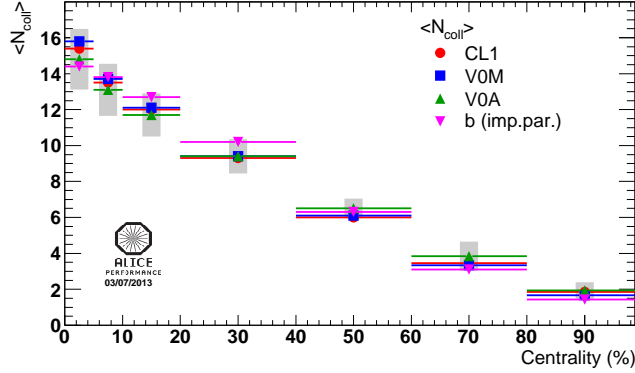


Figure 2: Values of  $N_{\text{coll}}$  extracted from CL1, V0M, V0A, ZNA and by slicing the hadronic cross-section from the impact parameter distribution.

### 3. Bias in the centrality measurement

In order to use these  $N_{\text{coll}}$  values in a  $R_{pA}$  calculation, one needs to understand the bias arising when sampling the pA events in centrality classes. There is a much looser correlation between impact parameter and  $N_{\text{coll}}$ , and between  $N_{\text{coll}}$  (or  $N_{\text{part}}$ ) and the charged particle multiplicity for p-Pb than for Pb-Pb collisions. Also the correlation between different multiplicity estimators is much broader in p-Pb than in Pb-Pb. The width of the correlations demonstrates the importance of fluctuations, when centrality is defined based on particle multiplicity, resulting in a bias of the p-N collisions in a given centrality class.

Directly from the NBD-Glauber fit an indication on the strength of these bias can be derived. Fig. 3 shows the ratio of the generated multiplicity per particle source divided by the mean multiplicity of the NBD. In case of p-Pb, particle sources correspond to  $N_{\text{part}}$ , while for Pb-Pb, they are a function of  $N_{\text{part}}$ . This ratio is constant in case all collisions are unbiased. However the plot shows a function of the centrality indicating a positive (negative) bias in central (peripheral) events, much larger compared to what obtained in Pb-Pb collisions, where the width of the plateau of the ancestor distribution is large with respect to multiplicity fluctuations, and only the most peripheral events are biased, due to their small multiplicities.

To interpret this result Monte Carlo generators that correctly simulate multiparticle production in nucleon-nucleon collisions are needed. In all recent Monte Carlo generators, for example HIJING [7], a large part of the multiplicity fluctuations is due to the fluctuations of the number of particle sources via multiple parton interactions (MPI). Therefore, the biases on the multiplicity corresponds to a bias on the number of hard scatterings in the event. For peripheral (central) collisions we expect a lower (higher) than average number of hard scatterings corresponding to a nuclear modification factor  $R_{pA}(p_T) < 1$  ( $R_{pA}(p_T) > 1$ ).

In most cases, the MPI probability is governed by the impact parameter be-

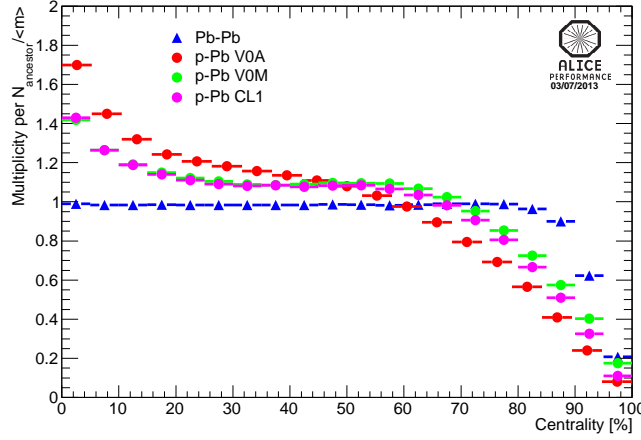


Figure 3: Multiplicity fluctuation bias calculated from the NBD-Glauber MC as the ratio between mean multiplicity per ancestor and the mean NBD multiplicity in p-Pb and Pb-Pb calculations.

105 tween two nucleons. The mean nucleon-nucleon impact parameter as a function of the number of participants can also be directly obtained from a Monte-Carlo Glauber simulation and is shown here. For collisions down to  $N_{\text{part}} \approx 4$ , it is constant but increases significantly for peripheral collisions. In peripheral collisions, the multiplicity bias which gives a lower (higher) than average number of hard  
 110 scatterings for peripheral (central) collisions is further enhanced by the higher than average nucleon-nucleon impact parameter, that reduces the probability for MPI.

Concerning the nuclear modification factor  $R_{pA}$  at high transverse momentum another type of bias has to be discussed. This affects only the most peripheral events. High momentum particles are produced in the fragmentation  
 115 of partons produced in parton-parton scattering with large momentum transfer. These fragmentation products contribute to the overall event multiplicity and this can introduce a trivial correlation between the centrality estimator and the presence of a high momentum particles in the event. Specifically, a cut of the  
 120 most peripheral p-Pb collisions (e.g. 80-100%) selects a range in multiplicity smaller than the multiplicity range covered in pp, therefore resulting in an effective veto on the large multiplicity events produced by hard processes. Here, the multiplicity estimator acts also as a veto on hard processes which contribute to the overall multiplicity (jet-veto).

#### 125 4. Implications for binary scaling

Practically for the different estimators used we expect different deviations from  $N_{\text{coll}}$  scaling, namely:

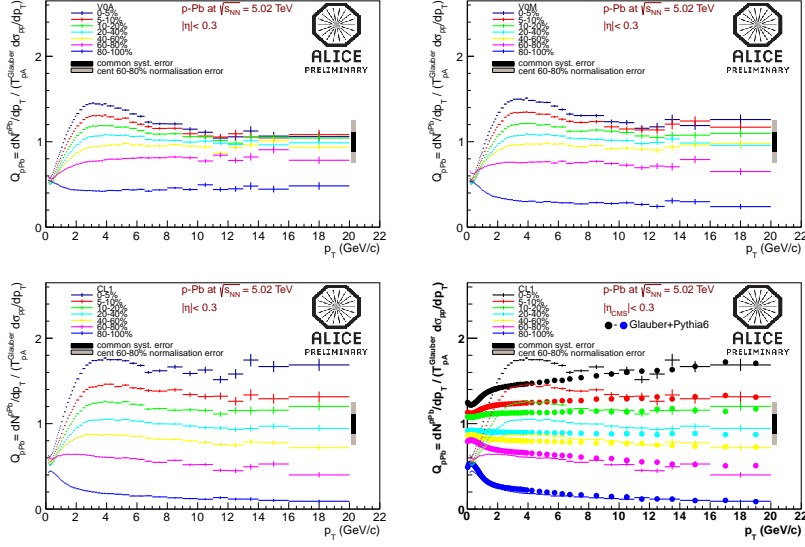


Figure 4:  $Q_{pA}$  of all charged particles for various centrality classes obtained with different centrality estimators: V0A (top left), V0M (top right), CL1 (bottom left). Bottom right: The spectra for CL1 are compared to the one obtained with the Toy-MC (Pythia + Glauber).

- CL1 (Clusters Pixel Layer 2): strong bias due to full overlap with tracking region. Additional bias in peripheral event from Jet veto effect since jets contribute to the multiplicity and shift events to higher centralities ( $p_T$ -dependent).
- V0M (V0A+V0C) Multiplicity: reduced bias since it is outside the tracking region
- V0A Multiplicity: reduced bias because of the important contribution from Pb fragmentation region.
- ZNA: small bias since the slow nucleon production is independent of hard processes.

In general, the number of binary collisions  $N_{\text{coll}}$  is used to scale the reference pp yields and obtain the nuclear modification factor. However, from the discussion above, it is expected that observables measured in centrality classes based on particle multiplicity deviate from binary scaling leading, at high momenta, to nuclear modification factors  $R_{pPb} < 1$  ( $R_{pPb} > 1$ ) in peripheral (central) collisions. These effects are enhanced in peripheral events by the jet-veto and the rising mean impact parameter. Therefore we define  $Q_{pA}$  for "centrality" selected data, as biased ratios, therefore to be denoted by Q, not R, and constructed as:  $Q_{pA}^{\text{range;EST}} = \text{Yield}(pA)^{\text{range;EST}} / \langle N_{\text{coll}}(\text{Glauber}; \text{EST}) \rangle \times \text{Yield}(pp)$ , each biased by the use of the particular estimator EST for the event ordering.

Figure 4 shows the  $Q_{pA}$  for different centrality estimators and different centrality classes. For all centrality classes  $Q_{pA}$  strongly deviates from unity at high  $p_T$ , with values at high  $p_T$  well above unity for central collisions and below unity for peripheral collisions. However the spread between centrality classes reduces with increasing rapidity gap between the centrality estimator and the  $p_T$  measurement, namely it is largest for CL1, reduces for V0M and even further for V0A. The smallest bias is present for the ZNA measurement. There is a clear indication for the jet-veto bias in the most peripheral CL1 class  $Q_{pA}$  has a significant negative slope due to the fact that the contribution of jets to the overall multiplicity increases with  $p_T$ . This jet-veto bias diminishes in V0M and is absent in V0A, where however  $Q_{pA} < 1$ , indicating that the multiplicity bias is still present. The smallest bias is expected from the ZNA, the analysis of which is still in progress.

The mean  $Q_{pA}$  at high  $p_T$  with the various estimators shows the same centrality dependence as seen in multiplicity bias (NBD-Glauber fit). If we model p-Pb collisions as incoherent superposition of nucleon-nucleon by coupling in a Toy-MC a Pythia [8] simulation to our Glauber calculation, we can estimate the trend of hard scatterings per collision as a function of centrality. This multiplicity bias shows a strong deviation from  $N_{\text{coll}}$ -scaling at low and high centralities with dependence very similar to the mean  $Q_{pA}$  at high momenta. The shape flattens with increasing rapidity gap, going from CL1 to V0M and finally to V0A.

Therefore we compare the measured  $Q_{pA}$  for the CL1 estimator to the one obtained with the Toy-MC (Pythia + Glauber). The bias at high  $p_T$  is described by incoherent superposition of pp collisions, for all centralities. For most peripheral, there is good agreement also in low- and intermediate  $p_T$  region. But at low- and intermediate  $p_T$  region strong deviations are observed for all other centrality bins, which can be presumably attributed to nuclear modification effects, observed in other physics observables.

## 5. Conclusions

In summary, centrality estimators based on multiplicity measurements in  $|\eta| < 5$  induce a bias on the hardness of the pN collisions that can be quantified by the number of hard scatterings per pN collision. Low (high) multiplicity p-Pb leads to lower (higher) than average number of hard scatterings. This bias can be quantified with a toy MC that builds an incoherent superposition of pN collisions and nuclear modification effects should be searched including this bias. For "centrality" selected data, for which  $\langle N_{\text{coll}} \rangle$  is not uniquely defined, we introduced  $Q_{pA}$ 's, each biased by the use of the particular estimator for the event ordering. A selection based on the ZDC provides a measurement with minimal (or absent?) bias, for which should be possible to calculate an unbiased  $R_{pA}$ . There are on-going efforts in the ALICE Collaboration to understand  $N_{\text{coll}}$  from Slow Nucleon Model.

190 **References**

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